Precision Signal Power Measurement System Using Central Computing

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A Precision Signal Power Measurement System was built for research, development, and demonstration of a digital technique for the measurement of spacecraft signal power. Demonstrations at DSS 14 have shown that the method is valid. Since the process relies heavily on digital computations and computers are in short supply at deep space stations, it was necessary to determine if centralized computation could be done. To test this feasibility, the system described in this article was developed from existing subsystems and additional or new programs. During design of this system, parameters and relationships were developed to predict the behavior of the completed system.

Tests of this system in January 1971 showed that it performed as predicted. The final demonstration was conducted using the Mark IIIA hardware/software system in the Mission Control and Computing Center. The results indicate that remote processing of precision signal power measurement data is technically feasible. As implemented, the technique is limited to narrow-band spectra of signals with power levels between −140 and −170 dBm.

I. Background

A Precision Signal Power Measurement (PSPM) system was built for research, development, and demonstration. The PSPM system uses digital measurement of signal spectra for the determination of spacecraft downlink power (Refs. 1 and 2). Demonstrations of this local site system at Deep Space Station 14 (DSS 14) have shown that the method is feasible and reliable. The measurement variance was less than 0.5 dB for signals stronger than −175 dBm, as predicted by theory (Ref. 2). Since computing power (and space) are limited resources at DSSs, it was necessary to determine the feasibility of using a central computing facility.

The Mark IIIA system located at the Mission Control and Computing Center (MCCC) was chosen because it was already processing data from the DSSs (Ref. 3). Some of the data processed through the system are gathered by the Digital Instrumentation Subsystem (DIS) (Ref. 4) and sent over a high-speed data line (HSDL) at 4800 bits per second. This data rate is shared by 4 ports or devices, limiting the rate per device to 1200 bits per second.

The PSPM was integrated into the data processing network by adding programs to both the Mark IIIA and the DIS systems. A processor called the *Mariner Mars 1971 Precision Signal Power Measurement Program* (Ref. 5) was added to the Multimission Real-Time Flight Operations System, a program in the Mark IIIA (Ref. 3). The DSIF Monitor System Phase II program (Ref. 6) was modified to include PSPM data gathering (Ref. 7). This equipment, with its programs, was capable of doing the PSPM processing remotely. The results were the same as those obtained using the local site system.

The remote processing, however, has limitations. The measurement bandwidth is limited to 62 Hz by the HSDL. While the HSDL is able to send 1200 bits per second, not all of these bits are available for data; 326 bits are used for a header giving routing and a trailer containing error conditions and an error-detecting code. The bandwidth limitation places a bound of about -140 dBm on the strongest signal that can be measured accurately. The response of the Mark IIIA system, when fully loaded, is about 10 minutes. This means that 10 minutes will elapse after the last data point is sent before the results are received at the site. This delay is acceptable for monitoring, but would hamper "troubleshooting," an important benefit of the PSPM.

While the demonstration of the remote processing PSPM system has shown the technical feasibility of the approach, the feasibility is shown only for this configuration of equipment. Substituting the Network Control System (NCS) for the Mark IIIA would not be feasible, since the PSPM data rate from only one station would represent 20% of the channel capacity allocated to the NCS.

II. The PSPM Technique

The PSPM technique was derived from methods used for the radar exploration of Venus (Ref. 8). The technique is based on the determination of the signal-to-noise ratio (SNR) from the computed spectrum of a narrowband signal. The SNR together with the noise power present at the input of a receiver determine the power of the received signal. To perform this measurement, the signal from the receiver is sampled, converted to a digital value, and transformed into a power spectrum.

The Fast Fourier Transform (FFT) method is used to compute the complex spectrum from the samples of the signal. The power spectrum is then derived by squaring and adding the complex components for each spectral point. Since the signal is coherent with the sampling process and is stationary in frequency by the tracking action of the receiver, the location of the signal within the spectrum is known precisely. By summing the power in the two parts of the spectrum (that containing noise only and that containing signal plus noise), the SNR of the signal is determined. The SNR relates the strength of the signal to that of the noise at the input of the receiver. Knowing the noise power entering the receiver, the signal power can be computed.

The noise power is found by measuring the temperature at the input of the receiver. The temperature is converted to power by:

$$P = KTB$$

where

P = power, watts

K = Boltzmann constant (1.38054×10^{-23} watts/Kelvins-Hz)

T = temperature, Kelvins

B = bandwidth, Hz (one half of the sampling frequency)

The temperature is measured by a total power radiometer (Ref. 9), which in turn is calibrated by the Y-factor technique (Ref. 10). The Y-factor is the ratio of the power out of a receiver with noise added to that with no noise added, i.e.,

$$Y = \frac{P_a}{P_{sa}}$$

$$Y = \frac{(T_{sa} + T_a)(KBG)}{T_{sa}(KBG)}$$

where

P_a = power output, watts, when switched to the ambient load

P_{sa} = power output, watts, when switched to the antenna

T_{sa} = system temperature, Kelvins, defined at the maser input when switched to the antenna

T_a = system temperature, Kelvins, defined at the maser input when switched to the ambient load

K = Boltzmann constant (watts/Kelvins-Hz)

B = bandwidth, Hz

G = receiver gain

Solving for T_{sa}:

$$T_{sa} = \frac{T_a}{Y - 1}$$

T_a is measured with a quartz thermometer (Hewlett-Packard model 2801A). The accuracy of this instrument is better than 0.05°C (Ref. 11).

The frequency bandpass characteristics of the PSPM system can be compensated for by measuring the response of the system with white gaussian noise as its only input. The spectrum of this input, when normalized and divided into a normalized signal-plus-noise spectrum point-by-point, compensates for gain variations as a function of frequency (Ref. 8). With improvements in the hardware, the need for compensation has disappeared. The capability, however, has been retained in the Mark IIIA program.

III. System Hardware Configuration

The remote processing PSPM system (Fig. 1) was composed of several distinct units. Of the many pieces of equipment located at a DSS, only a few were used for the PSPM. The signal transmitted by a spacecraft was received and tracked by the DSIF closed-loop receiver. Output from this receiver was converted by the PSPM equipment into two data streams: narrow-band signal plus noise and wide-band total power. The narrow-band signal was derived from the received carrier by bandlimiting and translating to baseband. The entire IF signal was power detected to produce the total power data. These data streams were sampled by the DIS. The samples collected by the DIS were formed into blocks and transmitted to the MCCC over the HSDL. The data blocks were also recorded on digital magnetic tape at the site as backup. This backup tape is called an Original Data Record (ODR). Coherent signals for the receiver, PSPM equipment, and DIS were provided by the Frequency and Timing Subsystem (FTS).

The Mark IIIA system at the MCCC received and reformatted the blocks of data. The data were then routed to the PSPM processor within the IBM 360/75 computer. After calculation of values for power spectrum, average temperature, and signal power level, these values were returned to the site via the teletype (TTY) network and communications processor (CP), where they were printed on a page printer. The control console of the site and the manual entry device (MED) at the MCCC provided operator access to the programs for on-line real-time control.

In the future, the monitor functions will be handled by the NCS rather than the Mark IIIA. If PSPM is to be included, further tests will be required to determine the feasibility of using the NCS for PSPM remote processing. Such feasibility may be limited, since the data rate required by PSPM for each station represents about 20% of the present NCS channel capacity.

IV. System Software Configuration

As stated above, three distinct computers were used to support the PSPM system (see Fig. 1). Software for the DIS and 360/75 computers was either created or modified for this project. The third computer, a Univac 490 used as the communications processor, utilized the JACOMMS (Ref. 12) system. JACOMMS is a standard program for on-line communications tasks. The DIS computer normally runs the DSIF Monitor System Phase II Program. To meet the requirements of the PSPM system, this program was modified to become the PSPM Data Gathering Program (Ref. 7). The modifications did not impair or slow the other function of the program. A processor was written for the MCCC Mark IIIA system running in the Master Control and User Interface (MC&UI) environment (Ref. 13). This processor, the Mariner Mars 1971 Precision Signal Power Measurement Program (Ref. 5), was added to Model V of the Multimission Real-Time Flight Operations System.

The DSIF Monitor System Phase II Program was designed to provide a real-time monitor and display capability for a DSS and to communicate status information with the MCCC via the Ground Communications Facility and the HSDL. The PSPM data were presented to the DIS as analog voltages which were sampled under interrupt and stored in a table for transmission over the HSDL. The sampling interrupt was 50 pps derived from the FTS and was coherent with other frequencies in the receiver. Provisions were made in the program to control the PSPM sampling routine through an on-line control console. Commands were available to enable and disable the PSPM sampling routine, as well as the PSPM log tape (ODR). Other instructions were used to change the amount of data used for a calculation of signal power, initialize the HSDL, and handle the log tape.

The Mariner Mars 1971 Precision Signal Power Measurement Program (Ref. 5) was written in three parts:

the first converts and stores input data points; the second computes the power spectrum by the FFT method; and the last applies shaping, computes the power level, and outputs the results to the TTY network for transmission to the station (see Fig. 2).

One of the system functions residing in the JPL Operating System (JPLOS) interfaces hardware interrupt servicing routines to independent task management operations. This function looks at all real-time data and selects the appropriate task in the programming system to process the data. The routing function is told of these tasks through the DTROUTE macro instruction coded into the task. Thus, data arriving from the HSDL were sent to Part I of the PSPM program automatically by calling upon these system functions (Ref. 13, p. 3-6). Self-contained units of a program do not need to be resident in the active part of the 360/75 computer if they are connected to the main program through the RTATTACH facility of JPLOS (Ref. 13, p. 3-1, ff). To use this facility, the RTATTACH macro instruction is coded into the previous part of the program and calls the next part when it is needed. Parts II and III of the PSPM program made use of this facility. Data subpools held the information created by one part of the program that was to be used by another part. These subpools are labeled and protected areas of memory assigned to specific tasks through the RTATTACH facility. Noise calibration data, output spectra, and signal power levels were stored on mass disk memory pending their use.

The use of the DTROUTE and RTATTACH macros permitted the PSPM processor to be resident in the data base of the Flight Operations System and, at the same time, not require the services of the Mark IIIA unless PSPM data were actually being received for processing. This resulted in a data-driven real-time processor.

HSDL blocks containing 76 signal samples each were accepted by Part I of the program until 256 points had been received. These 256 points were then processed by the FFT of Part II to compute one estimate of the power spectrum. Successive estimates of the spectrum were accumulated. This process reduced the variance of the final result to a function of the number of samples used to compute it (Ref. 2). Provision was made, although not used in the demonstration, to shape the power spectrum by a window. Following this, the spectrum would have been corrected for frequency bandpass characteristics if it had been necessary. It was not necessary, since the ripple in the passband of the final filter was less than 0.1 dB (Ref. 2). The SNR was then computed from the adjusted spectrum and combined with the effective system temperature (T_{sa}) to give the signal power level. The results were sent to the communications processor, together with routing information, for delivery to the station over the TTY network.

Communications between the DIS and the Mark IIIA system were accomplished using the HSDL. The data were sent in a block of 1200 bits (Fig. 3). This block of data contained 120 bits of header information, 48 bits of sub-header information, as well as the T_{sa}, antenna angles, and signal data. A description of the standard HSDL header is presented in Ref. 14. Ground Communications Facility (GCF) error status and error control code information was added by the block multiplexer/demultiplexer equipment. This information is for errors introduced by the GCF during data transmission. The error status was checked by the Mariner Mars 1971 (MM'71) PSPM program, errors were noted, and a message code was sent in the teletype output to inform the operator of the errors. The calculation of the spectrum is highly tolerant of occasional errors in input signal data; therefore, no attempt was made to request retransmission of the data. This, however, is not true of errors which occur in the value of T_{sa}; therefore, an additional error code was included to signal this condition. Fig. 4 shows the TTY output message format. The date, time, serial number, DSS, quantity of data used (BU), and error codes (NOTE) are given in the first line. These values serve to label each measurement and identify the conditions surrounding it. SNR and signal power level (SPL) are the primary data contained in the second line. The temperature used in the calculations (TEMP) was also transmitted to the station. The RMS voltage of the signal plus noise presented to the DIS was given and could have been used to detect possible malfunctions of the equipment.

V. Design Parameters

The selection of noise bandwidth and analog-to-digital (A/D) resolution was determined by considering the effects of: (1) the range of the ratio of signal power to noise spectral density, R_N; (2) the maximum reasonable averaging time for a given variability in measurement; (3) the effect of quantization by the A/D converter on SNR; and (4) the limit to bandwidth imposed by the HSDL (874 bits per second). Two secondary factors were also included in setting the parameters: (a) available interrupt rate, and (b) word length (number of bits) of both the 360/75 and the 920 relative to packing and unpacking data.

The maximum bandwidth of the PSPM spectra in terms of the number of bits used per data point is given by:

$$B = \frac{\text{bit rate (max)}}{2\ell}$$

where bit rate (max) is set by the channel capacity of the HSDL, and ℓ is the number of bits per data point. Values for the conditions encountered are given in Table 1.

Taking, as an operating range, a signal power level of -140 to -170 dBm and T_{sa} of 15 to 50 K, as measured at DSS 14, the maximum and minimum R_N were computed from

$$R_N = \frac{S}{2KT}$$

where

S = signal power, watts

K = Boltzmann constant (watts/Kelvins-Hz)

T = temperature, Kelvins

The minimum R_N was found to be 14.5 (Hz); the maximum was 48.3×10^3 (Hz). (The unit Hz is included to show dependence upon noise bandwidth.)

The relationships between averaging time, signal power level, system temperature, signal and noise bandwidths, and the variance of the measurements are given by (Ref. 2):

$$t = \frac{1}{f_1}\left\{1 + \frac{f_2}{R_N}\left[2 + \frac{(f_1 + f_2)}{R_N}\right]\right\}\left(\frac{R}{\sigma_R}\right)^2$$

and

$$\Delta s = 10 \log\left(1 + \frac{\sigma_R}{R}\right)$$

where

t = averaging time, seconds

f_1 = noise bandwidth, Hz

f_2 = signal bandwidth, Hz

R_N = ratio of signal power to noise spectral density, Hz

R = measured value of R_N

σ_R = standard deviation in R

Δs = RMS error in $S_{(\mathrm{dBm})}$

This relationship was used to determine the parameters of the system under weak signal conditions. For the arbitrary design constraints of R_N (min) = 14.5 (Hz), $\Delta s \leq 0.25$ dB, and $f_1 = f_2 = 0.4B$, t was tabulated as a function of B (see Table 1). Seven or more bits per sample allow the system to meet the requirements with an averaging time of less than 2 minutes. This is a reasonable averaging time for the weak signal conditions.

The maximum computable SNR as a function of quantization is also tabulated in Table 1. This relationship is derived by comparing the noise power generated by quantization to the power of a sine wave with a peak amplitude equal to the maximum voltage that can be converted properly by the A/D converter. The noise of quantization is assumed to be a uniform random variable from -0.5 to $+0.5$. Thus,

$$P_s = \frac{2^{2(\ell-1)-1}}{Z}$$

and

$$P_{N_Q} = \frac{1}{12Z}$$

where

P_s = power of the sine wave

ℓ = number of bits in the A/D converter

Z = impedance of the circuit

P_{N_Q} = noise power due to quantization

A correction must be made if the peak voltage of the signal is less than the converter capability. The entire relationship is then:

$$R_{\max} = \frac{P_s}{P_{N_Q}}\left(\frac{E}{E_{\max}}\right)^2 = \left(\frac{E}{E_{\max}}\right)^2 \times 12 \times 2^{2(\ell-1)-1}$$

where

$R_{\max}$ = maximum computable SNR

E = peak voltage of the signal

$E_{\max}$ = peak converter voltage

Table 1 lists $R_{\max}$ for an $E_{\max}$ of 10 volts and an E of 3 volts.

The point at which the calculated R_N(max) matches or exceeds the R_N(max) required by the expected signals defines the parameters for the strong signal case. While the figures of Table 1 indicate that a system with a bandwidth of 62 Hz and a data word size of 7 bits would suit spacecraft applications, such a design would not allow for extension of the technique for either higher or lower signal power levels. To allow for extension, particularly in the strong signal limit, a 12-bit data word was chosen. Further, the bandwidth was set at 25 Hz since this was easily obtainable from the FTS. The characteristics of the system, as implemented, are shown on the last line of Table 1.

VI. Test Results

The remote processing PSPM system was tested under both simulated and real conditions. The tests show that the system, as it stands, performs as well as the local system. The simulated signal tests were conducted in two ways: (1) as a real-time tracking mission, and (2) as a retransmission or playback of mission data. The final test was conducted using signals from MM'71, processing them in a non-operational, but otherwise identical, Mark IIIA system. This system was also processing simulated Pioneer 10 and 11 data, resulting in a test/demonstration which was as close as possible to operating conditions.

Simulated data for the initial tests were generated at DSS 14. The characteristics of these data were measured and recorded with the same procedures used in the original demonstrations of the PSPM technique. After the calibration phase, the remote processing system was brought on-line and activated with the simulated signal. The simulated data that were transmitted to the MCCC were also recorded at DSS 14 as an original data record (ODR). This first test was remarkably successful in that all interfaces, both hardware and software, operated as expected. While the calculations of signal power were in error, the causes for these errors were identified before the end of the test. The ODR tape was used for subsequent simulated data tests using CTA 21 (Compatibility Test Area at JPL).

CTA 21 has a complement of equipment similar to that at a typical DSS. A capability exists for the retransmission of ODRs, making this JPL facility ideally suited for integration tests. The ODR tape recorded in the first test was used with the CTA 21 equipment to verify that the corrections were made properly and to smooth out the operational procedures for PSPM. A further advantage of the retransmission mode is that the data rate can be increased by a factor of six. This is done by transmitting 4 blocks of data per second on the HSDL, instead of 1 block for each 1.5 seconds. No problems were encountered, indicating that the speed of the MCCC computers would not limit the measurements at the design bandwidth. The ODR tape was also processed by an independently written program to verify further the remote processing activities. The independent program was written in Fortran on a Xerox 930 computer. A comparison of the results from both programs shows excellent agreement. (Table 2 gives a few points for illustration.)

VII. Conclusion

The final test/demonstration of the remote PSPM was conducted on January 21, 1972, from 21:30 to 23:00 GMT using the MM'71 spacecraft signal. The PSPM processor was built into Model V of the Flight Operations System, which was at that time under integration test and could not be used for operational mission support. It was, however, processing Pioneer data simultaneously with the MM'71 PSPM data. The results of this test are shown in Figure 5. Automatic-gain-control (AGC) values used for comparison were taken from the manually recorded values in the station performance report. The standard deviation of the PSPM measurements was 0.083 dB, as predicted in Ref. 2. The difference of approximately 1 dB between the two methods has occurred in other measurements and is under investigation.

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Table 1. Parameter tradeoff[a]

Number of bits per data point, ℓ	Bandwidth B, Hz	R_{max}	R_N (max) = $B \cdot R_{max}$	Averaging time t, seconds
1	437	.53	231.6	516
2	218.5	2.1	458.8	280
3	145.7	8.4	1224	228
4	109.3	33.8	3694	165
5	87.4	135	11.80×10^3	143
6	72.8	549	39.99×10^3	128
7	62.4	2205	137.6×10^3	119
8	54.6	8847	483.0×10^3	112
9	48.6	35.3×10^3	1.715×10^6	107
10	43.7	141×10^3	6.162×10^6	103
11	39.7	564×10^3	22.39×10^6	101
12	36.4	2.27×10^6	82.63×10^6	99
13	33.6	9.04×10^6	303.7×10^6	97
14	31.2	36.2×10^6	1129×10^6	96
15	29.1	144.8×10^6	4214×10^6	96
12	25.0	2.25×10^6	56.25×10^6	95

[a]R_N (max) must exceed 48.3×10^3 to satisfy design requirements.

Table 2. Comparison of results

Signal-to-noise ratio			Temperature, Kelvins			Signal power level, watts			RMS voltage, volts	
Calibration	Measured		Calibration	Measured		Calibration	Measured		Measured	
920	360/75	930	920	360/75	930	920	360/75	930	360/75	930
9.70	9.73	9.78	20.5	20.59	20.59	−158.50	−158.59	−158.57	1.99	1.99
1.10	1.09	1.14	20.6	20.61	20.61	−168.02	−158.08	−167.90	1.62	1.63
0.87	0.87	0.88	20.6	20.63	20.63	−168.07	−169.05	−169.04	1.58	1.58
0.12	0.12	0.12	20.6	20.62	20.62	−177.57	−177.51	−177.65	1.52	1.52
0.12	0.12	0.13	20.6	20.62	20.62	−177.64	−177.68	−177.20	1.51	1.51

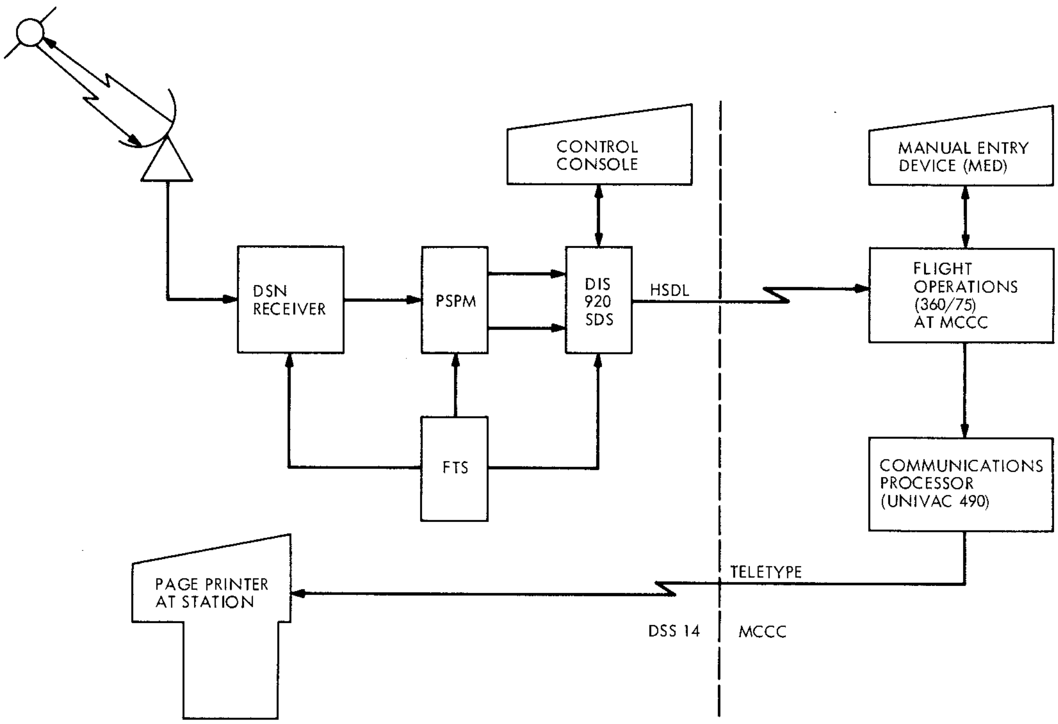

Fig. 1. Block diagram of remote processing PSPM system

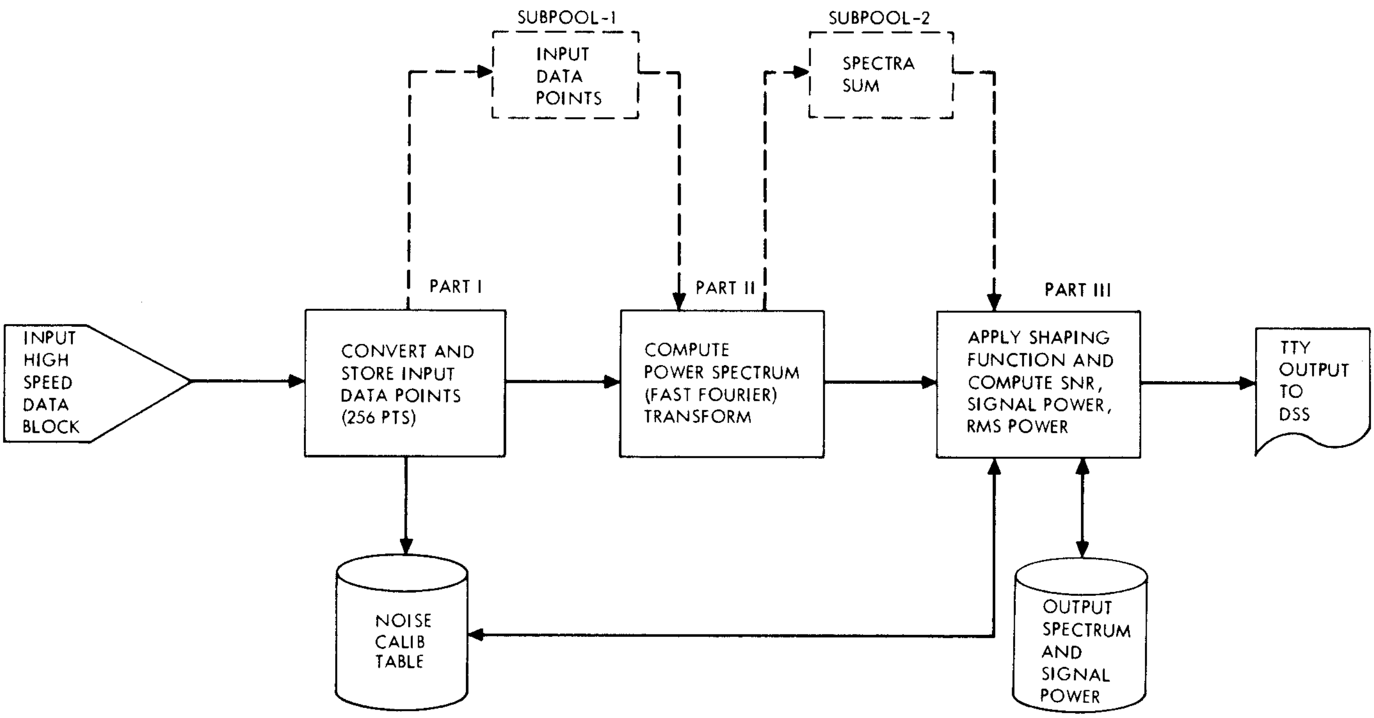

Fig. 2. Precision signal power measurement general program flow diagram

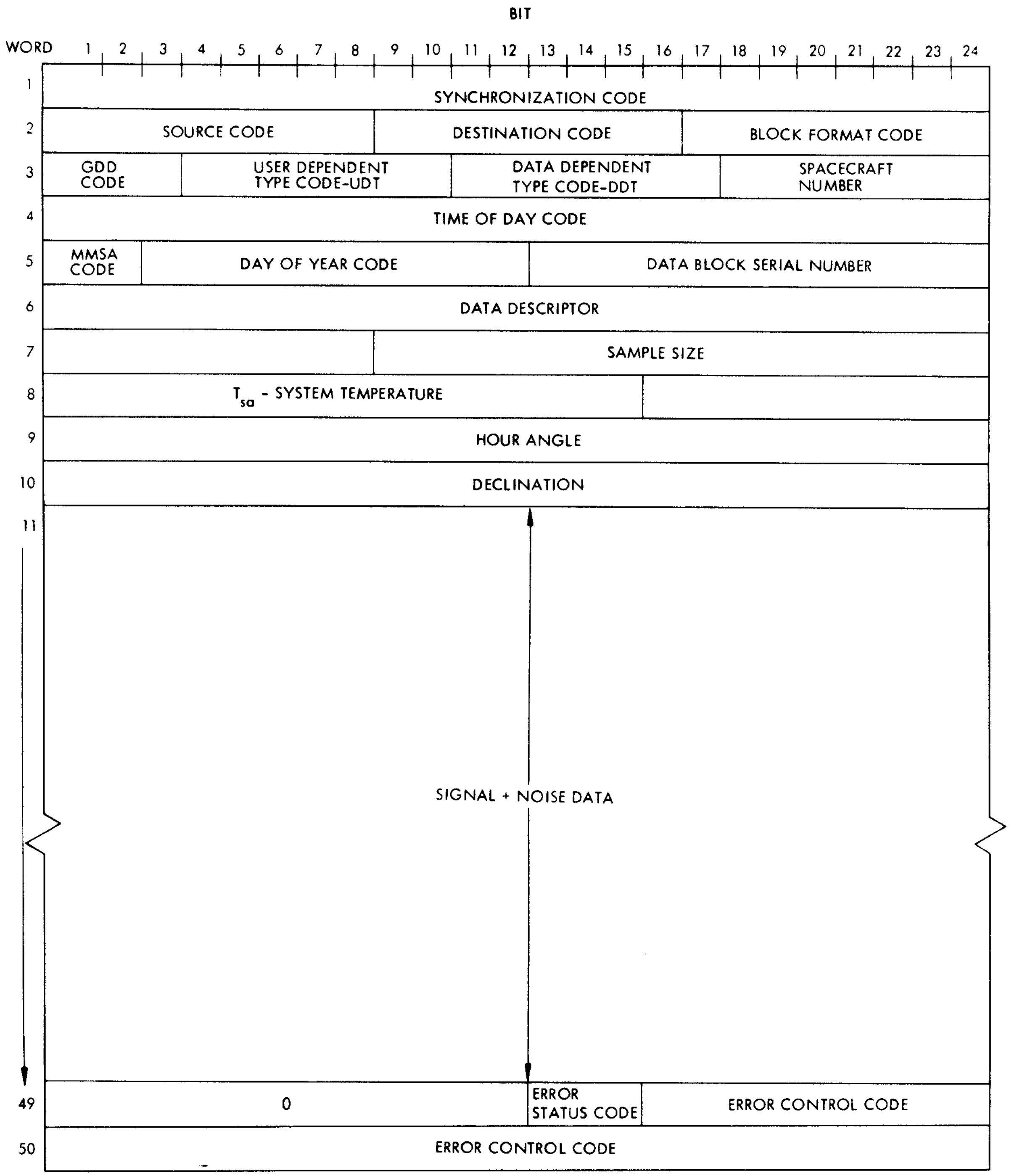

Fig. 3. Format of HSDL data block

```
PSPM XXX  DSS XX  DAY XXX  TIME XX/XX/XX   BU XXXX  NOTE XX-XXXX
 SNR XXXXXXX.XXXX, RMS V XXXX.XXXX, SPL XXXXX.XXXX, TEMP XXXX.XX
```

Fig. 4. TTY output message format

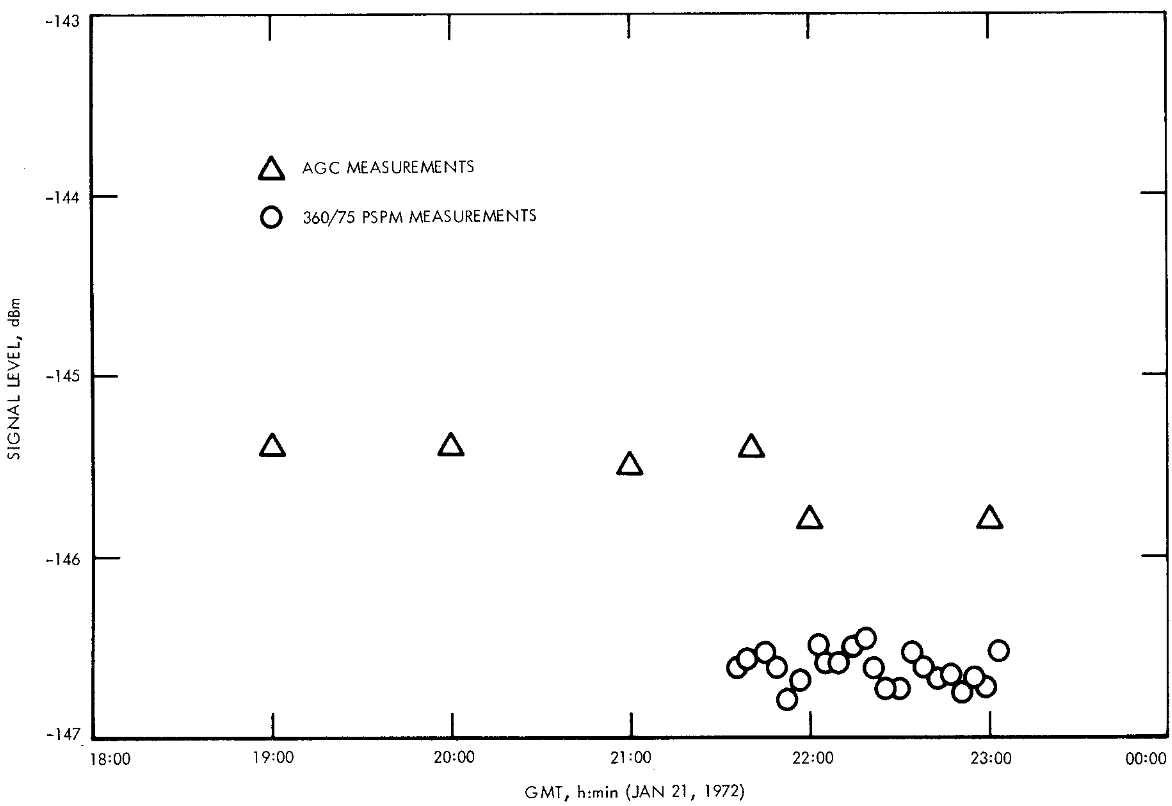

Fig. 5. Mariner Mars 1971 received signal power (AGC vs PSPM)